IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 4, Number 2, April 2012

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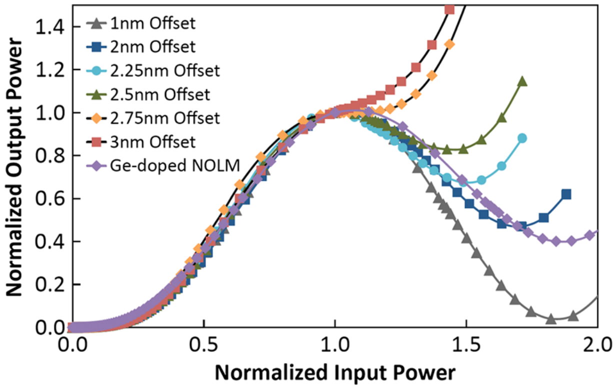

DOI: 10.1109/JPHOT.2012.2191770
1943-0655/$31.00

Power Transfer Function Tailoring in a Highly Ge-Doped Nonlinear Interferometer-Based All-Optical Thresholder Using Offset-Spectral Filtering

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DOI: 10.1109/JPHOT.2012.2191770
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Manuscript received February 7, 2012; revised March 11, 2012; accepted March 17, 2012. Date of publication April 3, 2012; date of current version April 6, 2012. This work was supported by the Princeton University School of Engineering and Applied Sciences, the Essig-Enright Fund, and the Lockheed Martin Advanced Technology Laboratory through their IRAD program, as well as the Lockheed Martin Corporation through their Corporate University Research Program. Corresponding author: N. S. Rafidi (e-mail: nrafidi@princeton.edu).

Abstract: We experimentally investigate and characterize the improvement in thresholding capability of a compact highly Ge-doped nonlinear interferometer-based all-optical thresholder using optical offset spectral filtering. The thresholder we study has an in-loop nonlinearity requirement lower than that of a classical nonlinear loop mirror scheme. Therefore, only 15 m of nonholey silica-based fiber is used as a nonlinear element. Although the nonlinear interferometer-based thresholder has been useful for signal regeneration and thresholding, it has several limitations, including severe pulse distortion due to pulse bifurcation at high input powers and a fixed power transfer function. In this paper, we propose and demonstrate the use of offset spectral filtering at the output of this Ge-doped low nonlinearity interferometer-based thresholder to adjust the power transfer function and thresholding slope, as well as reducing pulse distortion due to pulse bifurcation. To the best of our knowledge, this is the first experimental demonstration of power transfer function tailoring, which makes the thresholder more flexible and allows customization of thresholding parameters in meeting requirements in various systems.

Index Terms: Ultrafast nonlinear processes, fiber nonlinear optics, fiber optics systems.

1. Introduction

An effective technology for all-optical thresholding of ultrafast pulses is the well-known nonlinear optical loop mirror (NOLM) [1]. These devices use asymmetrical nonlinear phase shifts in highly nonlinear fiber (HNF) to achieve a polynomial power transfer function (power out v. power in). A nonlinear phase shift is induced by self-phase modulation in the HNF, which causes intensity-dependent interference in a joining coupler. The NOLM is a useful device for optical gating, wavelength conversion and optical code division multiple access networks [1]–[5]. Modified versions of the NOLM have been introduced with in-loop amplifiers or asymmetric loss [6] and an in-loop directional attenuator [7]. However, these schemes are quite bulky and have high latency because they typically consist of kilometers of nonlinear fiber. In addition, research has been conducted on improving the NOLM by changing the parameters of the fiber through the use of special devices or fiber twisting [6], [7], which complicate the settings and destroy the simplicity of the basic NOLM.

Among the various modified versions of NOLMs, [2] demonstrates a Ge-doped NOLM with a low requirement on the nonlinear phase shift, allowing the length of the nonlinear element to be shortened (only 15-m of highly Ge-doped nonlinear fiber is used). A tunable directional attenuator is also employed to allow precise and independent control of the amplitudes of the interfering components [2].

In this paper, we propose and demonstrate tailoring of the power transfer function of the Ge-doped NOLM with a low requirement on the nonlinear phase shift [2] using offset-spectral filtering. Here, we refer to this architecture as a "Ge-doped NOLM." Power transfer function tailoring makes the thresholder more flexible and allows customization of the thresholding parameters to the requirements of various systems. The Ge-doped NOLM is of particular interest because of the reduced nonlinear phase shift requirement, the short length of nonlinear fiber used, and the utilization of off-the-shelf passive components [2]. The above advantages are achieved through precise amplitude balancing of the loop to obtain complete destructive interference of the counter-propagating waves at the output port.

The use of offset-spectral filtering has been previously demonstrated in a classical NOLM with 1-km of HNF [8]. That paper discussed the tolerance to chromatic dispersion and noise reduction by examining the Q-factor and eye diagram improvement. However, that architecture did not include amplitude control of the counter-propagating waves, which resulted in inefficient interference and poor thresholding characteristics.

In this paper, we propose and demonstrate the use of offset spectral filtering at the output of the Ge-doped NOLM to adjust the power transfer function and the thresholding slope and to reduce pulse distortion due to pulse bifurcation. One of the drawbacks of the classical NOLM architecture is that it is difficult to adjust. That is, in the classical NOLM, the threshold level and shape of the power transfer function (input power versus output power) are predetermined by the physical setup and, thereafter, are not adjustable to meet the system requirements. By contrast, in the design proposed here, by adding a tunable optical bandpass filter at the output of a Ge-doped NOLM, the power transfer function can be tailored to suit any specific application. With proper adjustment of the center wavelength of the BPF, our Ge-doped NOLM with BPF combination has a more stable one-level region in its power transfer function without using a power limiter. Furthermore, we can tailor the power transfer function to suppress noise in both its zero and one regions. The power transfer function is a strong indicator of the ability of the thresholder to suppress noise and should ideally approach a step function. By adjusting the position of the BPF center wavelength relative to the input pulse center wavelength, we demonstrate a significant improvement in performance, evidenced by the polynomial order of the power transfer function as well as noise suppression in the measured eye diagrams. It has been demonstrated that NOLMs cause pulse bifurcation at greater-than-threshold powers [9]. This pulse splitting limits the NOLM's ability to be cascaded or be used in a system requiring feedback, such as in certain signal processing and computing applications. Pulse bifurcation in NOLMs also limits the throughput of systems using optical pulse position modulation to encode information. In our Ge-doped NOLM with BPF, the addition of a filter recovers the original pulse shape, which we have demonstrated via simulation using VPIphonics.

2. Operating Principles and Experimental Setup

Fig. 1 shows the architecture of our device. The modified NOLM consists of an asymmetric coupler (90:10), 15-m of highly Ge-doped nonlinear fiber (made of the preform 311cf HDF) [12], a tunable isolator, and a polarization controller. At the output of the modified NOLM, a tunable optical band-pass filter with a 3-dB bandwidth of 0.38 nm is used for offset spectral filtering. The optical band-pass filter is a three-stage Gaussian filter, where a filtering profile with steeper cutoff is expected to give a larger improvement in the power transfer function. As an input pulse source, we use a 1.25 GHz repetition rate mode-locked fiber laser generating $\sim$3 ps width pulses at the wavelength of 1551 nm. The laser output is amplified by an erbium-doped fiber amplifier (EDFA) to ensure nonlinearity is induced in the Ge-doped nonlinear fiber. Purple arrows correspond to the clockwise beam, while the orange arrows correspond to the counterclockwise beam.

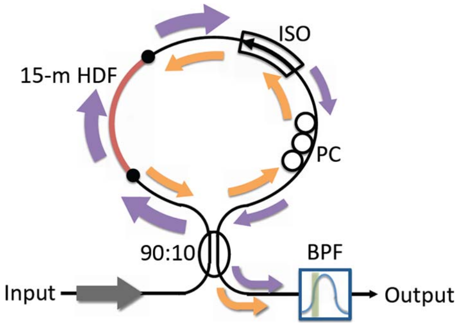

Fig. 1. Experiment setup of NOLM with BPF. BPF: Optical band pass filter, PC: polarization controller, ISO: tunable isolator; HDF: highly Ge-doped fiber (preform 311cf). Thicker arrows correspond to a larger power signal.

The Ge-doped NOLM is a Sagnac interferometer that measures the differential phase shift of the input pulse caused by the nonlinear phase shift in the HDF due to asymmetric splitting of the input. The input pulse is split into two counter-propagating pulses, one with 90% of the original power, and one with 10% of the original power. The size of the arrows in Fig. 1 represents the amplitude of the pulse the arrow describes. When each pulse reaches the nonlinear fiber, it incurs a phase shift proportional to its power. Thus, the stronger pulse has a significantly greater phase shift than the weaker pulse. The tunable isolator acts as a directional attenuator, allowing the weak pulse to pass and attenuating the counter-propagating strong pulse. The tunable isolator is tuned to balance the power of the counter-propagating pulses at the coupler output. Thus, when the two pulses meet at the coupler after completing the loop, they have the same power but different phases. The polarization controller allows for fine adjustment of the relative phase of the pulses, according to the Jones matrix. The interference is such that for low powers, they interfere destructively at the output, while for high powers (above the threshold level), they interfere constructively at the output. Due to self-phase modulation in the HDF ([12] preform 311cf, doped with 75 mol.% GeO_2) with large nonlinear coefficient of 35 $W^{-1}km^{-1}$, the optical spectrum at the output of the modified NOLM is broadened. The output is then passed to a tunable optical band pass filter for offset-spectral filtering. By off-setting the filter from the center frequency of the pulse, the pulses that are above threshold are selectively passed through the filter, as determined by the filter position, improving the thresholding capability of the device. Although a change in wavelength results after offset spectral filtering, the original wavelength can be restored through wavelength reconversion techniques.

To examine the improvement of the Ge-doped NOLM with a BPF compared to the Ge-doped NOLM alone, the bandpass filter's center wavelength is adjusted to achieve a step response for thresholding. The location of the filter center wavelength is extremely important in determining the efficacy of the thresholding. This determines the steepness of the slope of the resulting power transfer function, the flatness of high level transmission, and efficiency.

In order to characterize the performance of the Ge-doped NOLM with BPF thresholder, we plot the power transfer function, i.e., the output power versus input power, normalized in both x- and y-axes to the occurrence of the step (or threshold value). The parameters for characterizing the performance of the thresholder are i) polynomial order of the linear region in the power transfer function and ii) flatness of the low and high output power levels. See Fig. 2 for an illustration of these regions. In order to detect these regions we find the localized slopes of the power transfer function. When the slopes approach a constant value it determines the slope of the linear region. The region of higher power after the linear region is the high-level region. The power transfer functions are normalized to the start of this region. Polynomial order is measured by fitting a straight line to the linear region on a log-log plot. The slope of the fitted line is the polynomial order of the device. A high polynomial order is desirable, because that results in a better ability to distinguish between low and high signal values. This is balanced against the desire to have a stable high-level region after the threshold, and to suppress one-level noise.

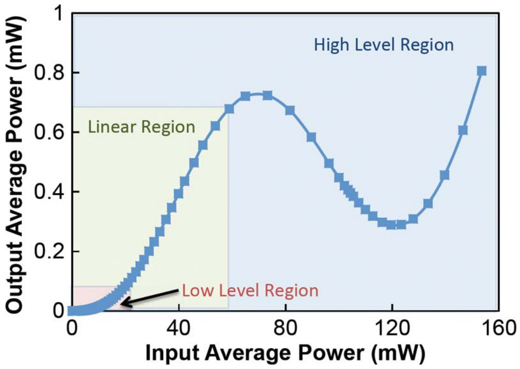

Fig. 2. Sample power transfer function, with pertinent regions labeled. This transfer function was taken for the Ge-doped NOLM device. The ideal power transfer function resembles a Heaviside step function, with 0 slope in the high and low level regions, and infinite slope in the linear region.

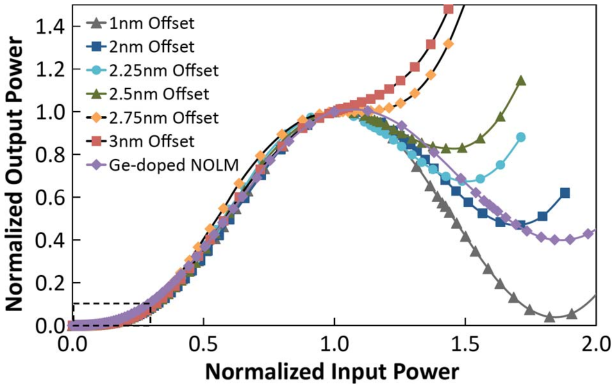

Fig. 3. Power transfer functions of Ge-doped NOLM and various offsets of the BPF. The numbers in the legend correspond with the offset of the center wavelength in nm of the BPF from 1551 nm for that data set.

3. Results

In our experiment, we performed a sweep using pulses of different input powers to get the power transfer function of our Ge-doped NOLM with BPF device and compare it to that of the Ge-doped NOLM alone, which we also obtained experimentally. The results are shown in Fig. 3. It is seen that the high level of the Ge-doped NOLM transfer function has a large variation in power, which limits the ability of the Ge-doped NOLM to suppress high-level noise. As the center wavelength of the bandpass filter moves further away from the input signal wavelength, a more stable high-level region results, which indicates that a better high-level noise suppression can be obtained. The experimental results indicate that a spectral offset between 2.5 nm to 2.75 nm yields the most stable high-level region. As for the low-level suppression, Fig. 4, which is an expansion of the low-level region of Fig. 3, shows that the use of BPF greatly enhances the performance of the Ge-doped NOLM, resulting in a flattened low-level region.

The thresholding ability of a given technology can be better quantified by examining the polynomial order of the linear region of the power transfer function, i.e., steepness of the slope, as shown in Fig. 5. Here, steeper slope is representative of better thresholding ability. The slope is taken from the curves shown in Fig. 3. As shown in Fig. 5, adding a BPF to the Ge-doped NOLM makes the slope of the thresholder much steeper, and a larger offset in spectral filtering results in a steeper slope in the transfer function, indicating a better thresholding ability despite the decrease in power efficiency of the device. We have simulated and studied how the change in BPF bandwidth affects

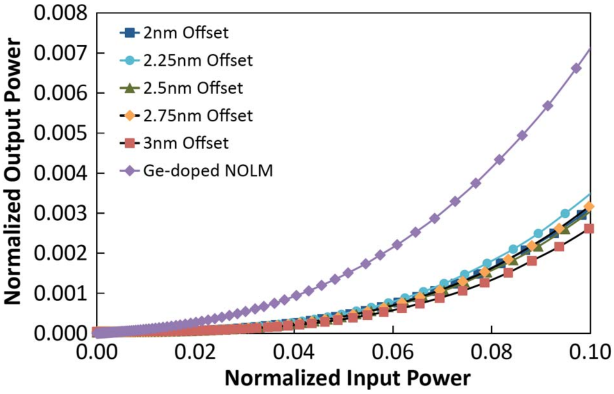

Fig. 4. Low-level region of the power transfer function, showing that a better low-level performance is obtained with the Ge-doped NOLM with BPF.

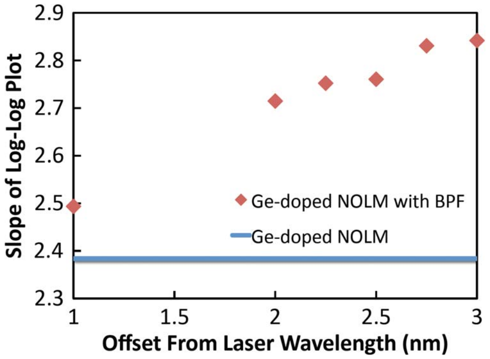

Fig. 5. Polynomial order, the slope taken from a linear fit to a log-log plot of the linear region of Fig. 4. The horizontal line marks the order of the power transfer function of the Ge-doped NOLM.

the power transfer function. Despite the decrease in output power, we observed that a narrower bandwidth results in a flatter low level region as well as a steeper slope, while the flatness of the high-level region evolves as the bandwidth of the filter changes. The evolution of high-level region flatness greatly depends on the input pulse profile, filter shape, as well as the wavelength offset of the bandpass filter.

We have also studied how the use of BPF improves the thresholding capability of Ge-doped NOLM by examining its effect on a noisy eye diagram experimentally. This helps put Figs. 3 and 5 in a different perspective, showing the overall effect of the shape of the power transfer function on the signal-to-noise ratio. Fig. 6 shows the eye diagrams of a) a noisy input, b) output after the Ge-doped NOLM, and c) output after the Ge-doped NOLM with BPF. The result shown in Fig. 6, captured with a 30-GHz oscilloscope, demonstrates that offset-spectral filtering can greatly improve the thresholding performance. Fig. 6(a) shows the input signal with pseudorandom binary sequence (PRBS) pattern, which has been corrupted by improperly biasing the electrooptic modulator to introduce noise to the signal and undesired level at the zero-level. Fig. 6(b) shows the signal after the Ge-doped NOLM, where moderate improvement is obtained with residue noise at both high and low levels. Fig. 6(c) shows the pulse after the Ge-doped NOLM with BPF, which has greatly reduced noise, flattening both the bit 1 and bit 0 levels. This demonstrates that the use of offset-spectral filtering using an optical BPF significantly improves the performance of the Ge-doped NOLM.

Fig. 7 shows the result for improvement in pulse bifurcation by applying offset spectral filtering after the Ge-doped NOLM. The simulation model included a Ge-doped NOLM with a 0.38-nm bandwidth bandpass filter, offset by 2 nm from the central input wavelength. In the simulation, a 5-ps

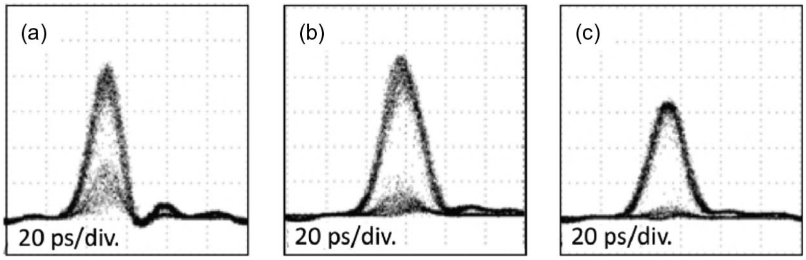

Fig. 6. Eye diagram comparison. (a) The input signal to the system. Noise was added before the Ge-doped NOLM. (b) Signal after the Ge-doped NOLM. (c) Signal after Ge-doped NOLM with BPF configuration.

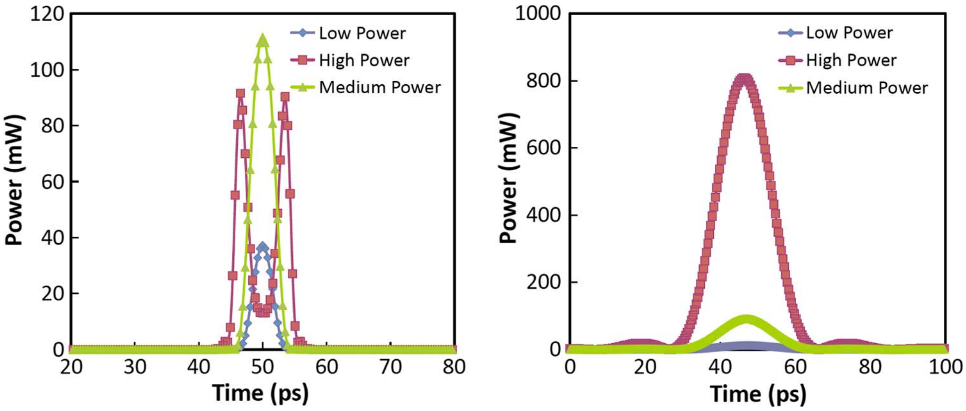

Fig. 7. Simulation results for improvement in pulse bifurcation using Ge-doped NOLM with BPF. Three pulses are in the low, linear, and high region of the power transfer function in accordance with amplitude. (a) Pulse shapes outputted by the Ge-doped NOLM. (b) Pulse shapes outputted by the Ge-doped NOLM with BPF.

wide pulse is used as the input. Offsetting the filter from the central wavelength corrects pulse bifurcation and thus improves overall device performance.

In the experiments, we were unable to measure pulse profiles directly due to the limited bandwidth of the oscilloscope (see Fig. 7). As shown in Fig. 7(a), pulse bifurcation does not occur in the low power configuration; however, as the power increase, the pulse split into two parts, as shown by the red square data points. With the use of offset-spectral filtering, no pulse bifurcation is observed, as shown in Fig. 7(b). However, the pulse width is significantly broader because of the narrow passband of the BPF, the pulse has a larger spectral width than the BPF passband. Therefore, input pulses were not perfectly restored at the output. However, this experimental limitation does not diminish our results, as the improvement we can get from the Ge-doped NOLM with BPF configuration is more significant. The pulse width can be restored through post-compression of the output pulse.

4. Conclusion

We demonstrated and studied power transfer function improvement and thresholding capability enhancement of a compact highly Ge-doped nonlinear interferometer-based all-optical thresholder using optical offset spectral filtering. This Ge-doped NOLM has in-loop nonlinearity requirement lower than for the classical nonlinear loop mirror scheme, such that only a short piece of Ge-doped nonlinear fiber is used. With the proposed Ge-doped NOLM with BPF configuration, the power transfer function is significantly improved, in terms of the steepness of the slope, as well as the flatness of the high and low levels, which has been shown experimentally in this paper. The Ge-doped

NOLM with BPF also has an improved performance measured by the eye diagram, where the residual noise after passing through the Ge-doped NOLM is further suppressed through offset-spectral filtering. Furthermore, the use of the filter corrects pulse distortion resulting from pulse bifurcation created by the Ge-doped NOLM, which we have shown through simulation.

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